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Article

A novel multivariate approach for biomechanical profiling of stair negotiation

Thijs M.A. Ackermans[a,*], Natasha C. Francksen[a], Raul V. Casana-Eslava[b], Carolyn Lees[c], Vasilios Baltzopoulos[a], Paulo J.G. Lisboa[b], Mark A. Hollands[a], Thomas D. O'Brien[a], Constantinos N. Maganaris[a]

[a] Research to Improve Stair Climbing Safety (RISCS), Faculty of Science, School of Sport and Exercise Sciences, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom;
[b]Faculty of Engineering and Technology, School of Applied Mathematics, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom;
[c]Faculty of Education, Health and Community, School of Nursing and Allied Health, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom;

*Corresponding author at: Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Tom Reilly Building, Byrom Street, Liverpool L3 3AF, United Kingdom. (T.Ackermans@2016.ljmu.ac.uk)

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Abstract

Stair falls, especially during stair descent, are a major problem for older people. Stair fall risk has typically been assessed by quantifying mean differences between subject groups (e.g. older vs. younger individuals) for a number of biomechanical parameters individually indicative of risk, e.g., a reduced foot clearance with respect to the stair edge, which increases the chances of a trip. This approach neglects that individuals within a particular group may also exhibit other concurrent conservative strategies that could reduce the overall risk for a fall, e.g. a decreased variance in foot clearance. The purpose of the present study was to establish a multivariate approach that characterises the overall stepping behaviour of an individual. Twenty-five younger adults (age: 24.5±3.3 y) and 70 older adults (age: 71.1±4.1 y) descended a custom-built instrumented seven-step staircase at their self-selected pace in a step-over-step manner without using the handrails. Measured biomechanical parameters included: 1) Maximal centre of mass angular acceleration, 2) Foot clearance, 3) Proportion of foot length in contact with stair, 4) Required coefficient of friction, 5) Cadence, 6) Variance of these parameters. As a conventional analysis, a one-way ANOVA followed by Bonferroni post-hoc testing was used to identify differences between younger adults, older fallers and non-fallers. To examine differences in overall biomechanical stair descent behaviours between individuals, k-means clustering was used. The conventional grouping approach showed an effect of age and fall history on several single risk factors. The multivariate approach identified four clusters. Three clusters differed from the overall mean by showing both risky and conservative strategies on the biomechanical outcome measures, whereas the fourth cluster did not display any particularly risky or conservative strategies. In contrast to the conventional approach, the multivariate approach showed the stepping behaviours identified did not contain only older adults or previous fallers. This highlights the limited predictive power for stair fall risk of approaches based on single-parameter comparisons between predetermined groups. Establishing the predictive power of the current approach for future stair falls in older people is imperative for its implementation as a falls prevention tool.

Keywords: stair descent; aging; fall risk; clustering; stepping behaviour

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Abbreviations *CoM: Centre of mass; CoP: Centre of pressure; CP: Cluster profile; PFLCS: Proportion of foot length in contact with stair; K: Optimal number of clusters; NHS: National health service; RCOF: Required coefficient of friction; SD: Standard deviation; SSQ: Sum of squares*

1. Introduction

Falls are a major problem for older adults, resulting in a significant financial and social cost to the individual and their caregivers. In addition, falls place escalating demands on the National Health Service (NHS) and the Social Care System (Scuffham and others 2003; Startzell and others 2000). The individual consequences of falling for an older adult include loss of independence and physical injury that could eventually lead to death (Scuffham and others 2003; Startzell and others 2000).

Stair falls account for approximately 20% of all falls and are the leading cause of accidental death in older people (Jacobs, 2016; Startzell and others 2000). To better understand the mechanisms underlying stair falling in older people and develop evidence-based interventions for improving stair safety, stepping biomechanics has been studied extensively (Buckley and others 2013; Christina and Cavanagh 2002; Hamel and others 2005; Mian and others 2007a; Mian and others 2007b; Templer 1995; Zietz and others 2011). The approach typically adopted has been to compare predetermined groups, for example older vs younger individuals (Christina and Cavanagh 2002; Hamel and others 2005; Mian and others 2007a; Mian and others 2007b), and fallers vs non-fallers (Zietz and others 2011), for given biomechanical parameters indicative of risk. For stair descent, which accounts for approximately 75% of all stair falls (Svanström 1974) a fall may be caused by trip, slip or loss of the centre of mass (CoM) control when stepping down (Templer 1995). Research indicates that the risk for a trip increases when the foot clearance from the step edges decreases or the variability of foot clearance increases (Hamel and others 2005; Roys 2001). It has also been shown that a decreased proportion of foot length in contact with the stair or increased required coefficient of friction (RCOF) increases the risk for a slip when placing the foot on the step (Christina and Cavanagh 2002; Roys 2001). The risk for a loss of CoM control increases when the centre of mass (CoM) acceleration increases or with an increased separation of the CoM and the centre of pressure (CoP) when stepping down (Buckley and others 2013; Mian and others 2007a; Mian and others 2007b; Templer 1995).

In several studies, older adults displayed not only riskier strategies, but also more conservative strategies when descending stairs. For example, high risk older adults have been found to display not only a decreased foot clearance, which increases fall risk, but also a decreased cadence, which indicates a more conservative strategy that could reduce the risk for a fall (Zietz and others 2011). Buckley (2013) showed that the increased risk for a fall due to a diminished ability to generate high eccentric ankle torques of older adults was accompanied by a reduced peak downwards CoM velocity, a more conservative strategy that could reduce the risk for a fall (Buckley and others 2013). In these examples, the conservative strategies adopted might mitigate the effect of the risky strategies and preserve stair safety. However, to generalise such a conclusion to a whole subject group assumes that both the riskier and more conservative strategies, identified by the inter-group comparisons, are displayed by the same individuals in the groups. At present, there is no evidence that the individual in a group with, for example, the smallest foot clearance is the same individual with the smallest variance in foot clearance. Therefore, individual stepping behaviour should be determined based on multiple parameters reflecting both risk and safety on stairs. However, such an approach has never been pursued before.

The purpose of the present study was to establish a multivariate approach for profiling individual stair negotiation behaviour during stair descent, avoiding the limitations introduced by comparing mean values of single outcome measures between predetermined groups.

2. Methods

2.1 Participants

Twenty-five younger adults (age: 24.5±3.3 y; body height: 1.74±0.06 m; body mass: 70.1±8.4 kg; mean and standard deviation (SD)) and 70 older adults (age: 71.1±4.1 y; body height: 1.68±0.08 m; body mass: 68.8±14.2 kg) participated in the study. All participants lived independently and were recruited from the local community of Liverpool, UK. Participants were excluded if they could not descend stairs in a step-over-step manner, or were using the handrails or any other aid to descend the stairs. Written informed consent was obtained from all participants after the procedures and possible risks of the study were explained. The study was approved by the NHS research ethics committee in the UK (IRAS ID: 216671) and was conducted in accordance with the Declaration of Helsinki.

2.2 Staircase configuration

The measurements were conducted on a custom-built instrumented seven-step staircase with four force platforms (1080Hz, 9260AA, Kistler AG, CH) embedded in the lower four steps (3-6) (Fig. 1). Kinematics were obtained using a 24 infrared camera system (120Hz, Vicon, Oxford Metrics, UK). The staircase configuration was set to represent a typical private home staircase in agreement with the building regulations in the UK (British-Standards-Institute 1984; Department-of-the-Environment-and-The-Welsh-Office 1992), with the rise (the vertical distance from one step to the next) set at 20 cm and the ‘going’ or run (the horizontal distance between the edges of adjacent steps) at 25 cm, resulting in a pitch of 38.7 degrees. Handrails on both sides of the staircase were in place during all tests (Fig. 1). The steps of the staircase as well as the top landing and walkway were independent structures (Fig. 1). The position of the top landing was fixed and the walkway was secured on the floor when placed in the desired position (i.e. the wheels were raised from the floor, so the wooden structure rested on the floor). The metal framework of the different steps was then connected by bolts to the top landing on one side, to the walkway on the other side, and to each other. As a result, the structures did not separate or roll away from each other.

[Please insert 'Figure 1' here]

2.3 Procedures

Participants descended the instrumented staircase at their self-selected pace in a step-over-step manner (i.e. alternative limb lead on each step) without using the handrails. Following a familiarisation trial we found that descending stairs step-over-step without handrail usage would not have been the self-selected strategy for some individuals. However setting the above constraints was necessary to standardise the task between individuals. Trials were performed with participants clothed in tight fitting Lycra shorts and shirt and wearing their own comfortable shoes (no boots, heels or sandals). All participants were fitted in a five point safety harness, which was attached to the overhead belay safety system. A trained member of the research team was attached to a rope on the floor and operated the rope of the belay system. The member of the research team made sure there was no tension in the rope and the rope was always behind the participant during the measurements. To allow familiarisation with the experimental setup and safety harness, participants performed up to five practice trials. After familiarisation, participants performed five more trials with the final three trials used for analysis. All participants had a break after the familiarization trial and were allowed to take as many breaks as they wanted during the following trials to avoid fatigue. In all trials, participants executed at least one step approaching the top of the stairs before stepping down and at least one step at the lower level away from the stairs.

2.4 Data analysis

Full body kinematics were obtained using a 15 segment (head, thorax, pelvis, upper arms, lower arms, hands, thighs, shanks, feet) full-body six-degree of freedom kinematic model defined by 76 reflective markers (diameter 14 mm). The segmental data were based on Dempster's regression equations (Dempster 1955) and used geometrical volumes to represent each segment

(Hanavan 1964). The position of the whole body CoM was estimated as the weighted sum of the various body segments using Visual3D (C-Motion, Germantown, USA). For further analysis all kinetic and kinematic data were filtered using a low-pass fourth order Butterworth filter with a cut-off frequency of 6 Hz. The gait events were determined using force plate data.

Kinetic and kinematic data were analysed to determine the following outcome measures:

i. *Maximal CoM angular acceleration*. This parameter reflects the ability to control the body against gravity as it descends and a higher acceleration is associated with a greater fall risk. The parameter takes both the CoM-CoP separation and the CoM acceleration into account, which are two known risk factors for a stair fall (Buckley and others 2013; Mian and others 2007a; Mian and others 2007b; Templer 1995). The angular acceleration was calculated for the angle (*a)* between the CoM and CoP position of the trailing leg (Fig. 2A). The maximal angular acceleration of the CoM was obtained as the peak value during the swing phase for steps 3-5 for all three trials as these represent steady state steps (McFadyen and Winter 1988). The mean value of maximal CoM angular acceleration across the three trials was considered for further analysis.

[Please insert 'Figure 2' here]

ii. *Foot clearance*. This parameter reflects trip-induced fall risk, where a smaller foot clearance is associated with a greater fall risk. The foot clearance was calculated by manually digitising the two-dimensional outline of the subject's shoe, which was obtained by taking a picture of the subject's shoe outline drawn on an A4 paper (Fig. 3A), using ImageJ (National Institutes of Health, Bethesda, USA). The coordinates of up to 600 virtual markers representing the individual shoe sole outline were then calculated in Matlab (R2018a, The Mathworks, Natick, USA) (Fig. 3B). The position of three markers fixed on the shoe of the subject (first metatarsophalangeal joint, fifth metatarsophalangeal joint and calcaneus lateralis) were digitized in the two-dimensional drawing and using the static measurement, which included the position of the three markers in a three-dimensional space, the position of the virtual outline of the shoe relative to the markers could be determined. The virtual outline of the shoe was then projected in the movement trials, again relative to the three markers (Fig. 3C). The foot clearance was obtained during the swing phase when the virtual shoe outline of the leading limb passed the vertical position (*a*) of the step edge up until the outline passed the horizontal position of the step edge (*b)* (Fig. 3D). The minimal clearance of the virtual shoe (dashed arrow in Fig. 3D) was determined within this time frame (*green* shaded area in Fig. 3D) and thus, could be the horizontal foot clearance, the vertical foot clearance or a resultant of the two in-between. The minimal foot clearance was determined for steps 1-5 in all three trials. The mean value across the three trials was considered for further analysis.

[Please insert 'Figure 3' here]

iii. *Proportion of foot length in contact with stair (PFLCS).* This parameter reflects slip-induced fall risk due to foot positioning relative to the step edge, where a reduced PFLCS is associated with a greater fall risk. PFLCS was calculated using the rigid virtual shoe outline introduced above (orange line in Fig. 2B), which was not influenced by foot deformation, at touch-down on steps 3-6 for all three trials (Fig. 2B). The parameter was calculated using the distance of the horizontal projection of the most posterior aspect (distance x) and the most anterior aspect (distance y) of the virtual shoe outline to the step edge (Fig. 2B). The PFLCS was calculated as a percentage using the following equation: PFLCS = (distance x / (distance x + distance y))*100% (Fig. 2B). The mean value of PFLCS across the three trials was considered for further analysis.

iv. *Required coefficient of friction (RCOF).* This parameter also reflects propensity for a slip between the shoe-surface interaction, as a higher friction is associated with a greater fall risk. It was calculated by dividing the resultant shear force (vector sum of the mediolateral and antero-posterior force) by the vertical force at each sample in time (Christina and Cavanagh 2002). The peak RCOF was determined during the loading phase of stance on steps 3-5 for all three trials using Visual3d (C-Motion, Germantown, USA) after a threshold of 50 N for the vertical force was exceeded to prevent erroneous results (Buczek and others 1990; Christina and Cavanagh 2002). The mean value of RCOF across the three trials was considered for further analysis.

v. *Cadence*. Descending stairs fast may result in a fall as an increased speed could negatively modify the four parameters above. The duration of one gait cycle was obtained for the right and left limb. Cadence was calculated as the average for the left and right limb for the three trials and the mean value was considered for further analysis.

vi. In addition to the five biomechanical parameters listed (i-v), *the trial-to-trial variance* values of these parameters for the three trials were calculated for each step separately. Higher variance between trials may indicate a person's inability to maintain a steady/safe movement pattern, which increases the risk for a fall (Hausdorff and others 2001). The trial-to-trial variance values for the steps were averaged and the mean value for each parameter (i-v) was used for further analysis.

2.5 Statistics

To investigate differences between the multivariate clustering approach and the common approach of single parameter comparisons using average group data, the analysed older adults were first classified into two groups (older fallers and older non-fallers) based on the occurrence of a fall in the past 12 months. A fall was self-reported and defined as an event that resulted in a person coming to rest inadvertently on the ground or floor or other lower level. A one-way analysis of variance (ANOVA) followed by Bonferroni post-hoc testing was used to identify differences in the biomechanical outcome measures between younger adults, older fallers and older non-fallers.

To examine differences in biomechanical stair descent behaviours between individuals (independent of age or fall history) k-means clustering was applied, a method that is typically used to differentiate categories or profiles (Lisboa and others 2013). First, the mean value of every participant for all outcome measures (i-vi) separately was normalised using Z score transformation. The method used to determine the appropriate number of k was the SeCo framework (Lisboa and others 2013), which has been previously described in detail (Casana-Eslava and others 2017; Chambers and others 2013; Lisboa and others 2013). Briefly, for a range of k values (k = 2-10), which represent the possible number of clusters created, K-means clustering was performed on the data 500 times. The centres of each cluster were reinitialised for each iteration. The total within cluster Sum of Squares (SSQ), which is a measure of separation, was calculated for each solution and the top 10% of these solutions was selected by the within cluster SSQ. The stability measure, the pairwise Cramérs' V statistic, was calculated for every pair of clustering solutions. This was used to determine the highest value of k before the stability of the clustering solutions breaks down. The Separation Concordance (SeCo) map that combined the separation and stability measure of these solutions was produced to determine the optimal number of clusters (k). To visualise the clusters in a three-dimensional space, a principal components analysis (PCA) was executed on the dataset and the first three principal components were plotted after the k-means clustering was completed. Furthermore, to examine differences in the composition of each cluster, the cluster profiles ($CP = (Mean_{cluster} - Mean_{overall}) / SD_{overall}$) were calculated for all outcome measures with a threshold set at 0.5.

Statistical analyses were performed using SPSS (version 24, SPSS Inc., California, USA) and Matlab (R2018a, The Mathworks, Natick, USA). The significance level was set at $\alpha = 0.05$.

3. Results

The one-way ANOVA revealed a group effect ($p<0.05$) for foot clearance, variance in foot clearance, PFLCS, variance in PFLCS, RCOF and variance in RCOF (Table 1). The post-hoc analysis (Table 1) revealed lower ($p<0.05$) mean and variance in foot clearance in younger adults compared to older fallers. In addition, the younger adults showed greater ($p<0.05$) variance in PFLCS and lower RCOF compared to the older non-fallers. The older fallers and older non-fallers showed greater ($p<0.05$) PFLCS compared to the younger adults. There were no statistical differences between older fallers and non-fallers.

[Please insert 'Table 1' here]

The stability and separation of the specified values of k, displayed in the SeCo map (Fig. 4), revealed that k=4 was the optimal number of clusters for the present dataset. This was in agreement with the visualization of the clusters using the first three principal components of the PCA, showing four segmenting clusters in the 3D environment (Fig. 5). All four clusters contained younger adults, older non-fallers and older fallers (Table 2). The CP (Table 3) with a threshold set at 0.5 revealed that cluster 1 differed from the overall mean by showing a higher CoM angular acceleration (CP = 1.19), more variance in CoM angular acceleration (CP = 1.48), lower RCOF (CP= -0.61) and a higher cadence (CP = 0.57). Cluster 2 differed from the overall mean by showing a higher foot clearance (CP = 0.85), more variance of RCOF (CP = 0.52) and a lower cadence (CP = -0.82) (Table 3). Cluster 3 differed from the overall mean by showing a higher foot clearance (CP = -0.57), less PFLCS (CP = -0.59), more variance in PFLCS (CP = 1.22), less RCOF (CP = -0.66), higher cadence (CP = 1.21) and more variance in cadence (CP = 2.60) (Table 3). In contrast, cluster 4 did not exceed the threshold and therefore did not show detectable differences in any of the parameters compared to the overall mean (Table 3).

[Please insert 'Table 2, 3 and Figure 4, 5' here]

4. Discussion

This study aimed, for the first time, to establish a multivariate approach that characterises the stair negotiation behaviour during stair descent based on multiple factors that include both biomechanically risky and conservative strategies. Four clusters were identified. Clusters 1-3 differed from the overall mean by showing both risky and conservative strategies on the biomechanical outcome measures, whereas cluster 4 did not display any particularly risky or conservative strategies in the biomechanical outcome measures compared to the overall mean. In contrast to the common approach of comparing single parameters between groups that showed an effect of age and fall history on several individual risk factors (Table 1), the multivariate approach showed that none of the clusters contained only (or all) older non-fallers or older fallers (Table 2). Instead, older fallers and older non-fallers were spread over the four clusters, as they did not present a similar particularly risky overall behaviour that would group them in the same cluster.

4.1 Traditional group comparisons

The commonly used comparisons between age and fall history groups showed that ageing had an impact on stair biomechanics during stair descent. The older adults who had a previous fall showed more variance in foot clearance compared to the younger adults (younger adults: 36.5 vs. older fallers: 68.2), which is a known risk factor for a trip on stairs (Hamel and others 2005). Moreover, the older adults who had not had a previous fall showed a greater RCOF compared to the younger adults (younger adults: 0.10 μ vs. older non-fallers: 0.11 μ); these increased frictional demands for the older adults might put them at a greater risk of a slip (Christina and Cavanagh 2002). These findings are in line with current literature showing that older adults display a more risky behaviour in several biomechanical outcome measures during stair descent (Christina and Cavanagh 2002; Hamel and others 2005; Mian and others 2007a; Mian and others 2007b). For the younger adults these biomechanical parameters indicate a more conservative strategy that could reduce the fall risk. In addition to the risky strategies above, the older adults had a greater foot clearance (younger adults: 20.1 mm vs. older non-fallers: 24.8 mm vs. older fallers: 29.8 mm), higher PFLCS (younger adults: 80.7 % vs. older non-fallers: 85.1 % vs. older fallers: 85.9 %) and less variance in PFLCS (younger adults: 18.4 vs. older non-fallers: 12.6 vs. older fallers: 15.2) than the younger adults. These are all biomechanical factors that indicate a more conservative strategy for the older adults compared to the younger adults and could potentially reduce the fall risk (Hamel and others 2005; Roys 2001). Furthermore, contrary to the differences in stair biomechanics between high risk and low risk older adults reported by Zietz (2011), our results revealed that a previous fall, which on its own is a risk factor for a future fall (Startzell and others 2000), had no impact on stair biomechanics (Table 1) (Zietz and others 2011). This discrepancy might suggest that the older fallers in the present study did not adopt more conservative stepping strategies during stair descent compared to older non-fallers. The results of the group comparisons suggest that both older and younger adults adopted not only biomechanically risky strategies, but also biomechanically conservative strategies that could mitigate the overall falling risk. However, based on these group means it cannot be established whether the individuals who adopted a riskier strategy, based on one parameter within a group, were the same individuals who adopted a more conservative strategy for another parameter.

4.2 Novel multivariate approach

The current multivariate clustering approach circumvents the above limitation and allows identification of the specific biomechanically risky and safer strategies that a particular individual exhibits. Three individual clusters (1-3) differed from the mean behaviour considering both the risky and the conservative strategies displayed. Cluster 1 differed from the mean by displaying a greater peak and variance in CoM angular acceleration, which both increase the risk for an of loss of CoM control when stepping down (Buckley and others 2013; Mian and others 2007a; Mian and others 2007b; Templer 1995). The greater cadence compared to the overall mean could increase the risk for a slip, trip or loss of CoM control. However, these riskier strategies were accompanied by a smaller RCOF, which is a more conservative strategy that could mitigate the risk for a slip (Christina and Cavanagh 2002). Cluster 2 differed from the mean by displaying more variance in the RCOF. More variance indicates a person's inability to maintain a steady movement pattern and could result in a slip (Hausdorff and others 2001). However, this increased risk for a slip was accompanied by a lower cadence, which is a more conservative strategy (Hamel and others 2005; Roys 2001), and a greater foot clearance, which decreases the risk for a trip. Cluster 3 was at increased risk for a trip due to a smaller foot clearance compared to the overall mean (Hamel and others 2005). There were also lower mean and variance values for PFLCS indicating a greater risk for a slip when placing the foot on the step (Roys 2001). In addition, cluster 3 had greater mean and variance values for cadence, which indicate an increased risk for a trip, slip or loss of CoM control. However, these differences in cluster 3 were accompanied by one conservative strategy when compared to the overall mean, namely a decreased RCOF that reduces the risk for a slip (Christina and Cavanagh 2002). Cluster 4 did not show any great differences from the overall mean. Therefore, cluster 4 did not show anything particularly risky, but also did not show any particularly conservative compensations. These findings show that the stair negotiation behaviour is based on a mix of biomechanically risky and safer strategies.

Furthermore, the four behaviours all contained older adults who had previously fallen (cluster 1: 3; cluster 2: 13; cluster 3: 2; cluster 4: 9; total 27 older fallers), at least one older adult who did not have a previous fall (cluster 1: 9; cluster 2: 17; cluster 3: 5; cluster 4: 12; total 43 older non-fallers) and at least one younger individual (cluster 1: 8; cluster 2: 1; cluster 3: 1; cluster 4: 15; total 25 younger adults) (Table 2). Therefore, we conclude that the younger adults, the older adult non-fallers and the older adult fallers did not present a similar overall behaviour per group that would assign them in the same cluster. This is in marked contrast with the commonly used grouping methods that differentiate cohorts based on fall-history and age to compare mean values for single outcome measures. The current approach allows profiling of overall stair fall risk based on multiple risky and conservative stepping strategies exhibited by the stair user.

The measurements of the present study were conducted on an experimental staircase using a safety harness in a lab environment, which differs from private home staircases and this might have had psychological effects on the stair performance of the participants. However, since the participants familiarised themselves with the experimental staircase and all were confident to negotiate the experimental staircase, we do not believe this was a substantial limitation.

At present, we are not able to quantify the effectiveness of the compensations or to determine which of the combined behaviours is safer for the older adults. Additionally, we are unable to state whether older adults who display no risky behaviour, but show an ‘average’ behaviour in all parameters (cluster 4), are at less risk for a fall. To reach this important conclusion, future research should implement the current method on older participants and link the clusters with some relevant metric for stair falls, for example number of stair falls and graded severity of the fall documented over a follow-up period. It is also important that further research aims to identify the specific functional deficits underpinning the biomechanically risky stepping strategies adopted, so that fall predictive and preventive programs can then be delivered to the older adults at risk.

5. Conclusions

In conclusion, for the first time a multivariate approach was able to characterise stair descent behaviour. In contrast to commonly used single-parameter comparative approaches, it was found that the older fallers and older non-fallers were spread over the four stepping behaviours identified. Three of the four identified behaviours were found to be a combination of biomechanically risky and safer components, whereas one ‘average’ behaviour without any particularly risky or safer characteristics was identified. Further research should implement this method on older adults using a longitudinal approach to identify the behaviours that can differentiate those who will go on to experience an actual stair fall from those who will not, so that targeted cost-saving interventions for improving stair safety in older individuals can then be designed and implemented.

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Tables

Table 1.

Mean (± SD) biomechanical outcome measures assessed for the younger adults, older non-fallers and older fallers.

	Younger adults (N=25)	Older adult non-fallers (N=43)	Older adult fallers (N=27)
Foot clearance [mm] *	20.1 ± 8.5 [a]	24.8 ± 9.4	29.8 ± 10.1
Var. foot clearance *	36.5 ± 21.9 [a]	48.1 ± 28.0	68.2 ± 53.6
PFLCS *	80.7 ± 6.2 [a, b]	85.1 ± 6.4	85.9 ± 7.9
Var. PFLCS *	18.4 ± 7.6 [b]	12.6 ± 7.4	15.2 ± 11.9
CoM ang. acc. [rad/s^2]	7.3 ± 3.4	6.6 ± 2.1	6.5 ± 1.7
Var. CoM ang. acc.	7.2 ± 5.9	7.0 ± 5.1	4.9 ± 3.4
RCOF [µ] *	0.10 ± 0.02 [b]	0.11 ± 0.02	0.10 ± 0.02
Var. RCOF (x 10^{-4}) *	2.2 ± 2.9	5.0 ± 6.0	5.8 ± 5.8
Cadence [cycle/s]	0.95 ± 0.10	0.91 ± 0.15	0.92 ± 0.18
Var. Cadence (x 10^{-3})	2.6 ± 3.0	4.6 ± 6.4	3.1 ± 3.0

Notes: *Var*: variance; *PFLCS:* proportion of foot length in contact with stair; *ang*: angular; *acc:* acceleration; *RCOF:* required coefficient of friction.

* Significant group effect (P<0.05)

[a] Significant difference between younger adults and older adult fallers (P<0.05)

[b] Significant difference between younger adults and older adult non-fallers (P<0.05)

Table 2.

Cluster composition of all four clusters.

	Younger adults (n=25)	Older adult non-fallers (n=43)	Older adult fallers (n=27)	Total (n=95)
Cluster 1	8	9	3	20
Cluster 2	1	17	13	31
Cluster 3	1	5	2	8
Cluster 4	15	12	9	36

Table 3.
Cluster profiles (CP) of the biomechanical outcome measures assessed for the four clusters. Those exceeding the threshold of 0.5 are highlighted bold and coloured in terms of risk (red = riskier strategy; green = more conservative strategy).

	Foot clearance	Var. Foot clearance	PFLCS	Var. PFLCS	CoM ang. acc.	Var. CoM ang. acc.	RCOF	Var. RCOF	Cadence	Var. Cadence
Cluster 1	-0.23	-0.36	0.17	-0.11	**1.19**	**1.48**	**-0.61**	-0.22	**0.57**	-0.10
Cluster 2	**0.85**	0.47	0.49	-0.42	-0.37	-0.43	0.49	**0.52**	**-0.82**	-0.35
Cluster 3	**-0.57**	0.38	**-0.59**	**1.22**	0.04	-0.37	**-0.66**	0.21	**1.21**	**2.60**
Cluster 4	-0.48	-0.29	-0.39	0.15	-0.35	-0.37	0.06	-0.37	0.12	-0.22

Notes: *Var*: variance; *PFLCS*: proportion of foot length in contact with stair; *ang*: angular; *acc:* acceleration; *RCOF:* required coefficient of friction.

Figure captions

Figure 1. *(2-column fitting image)*
A schematic representation (A) and image (B) of the custom-built instrumented seven-step staircase.

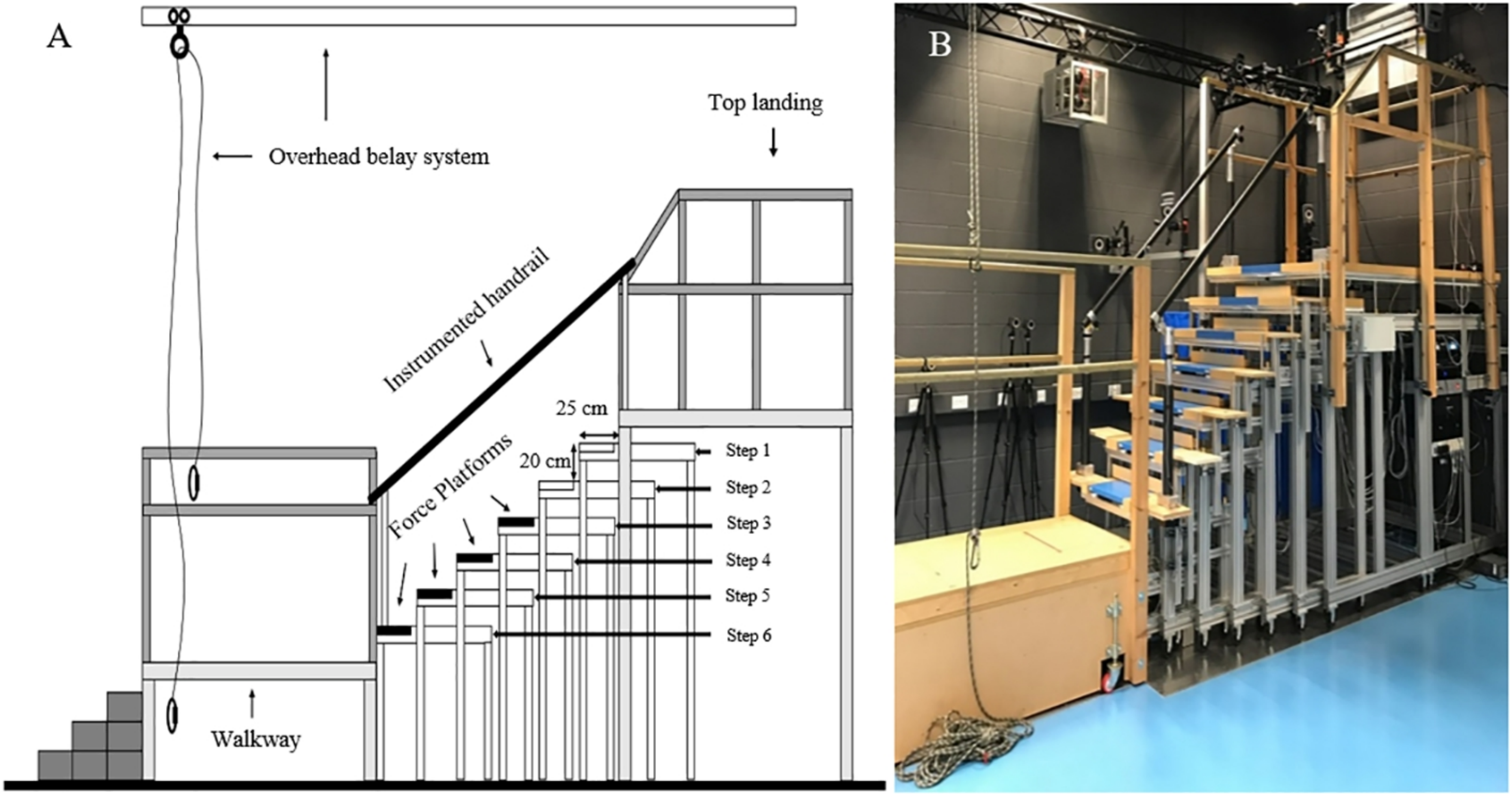
Figure 2. *(single column fitting image)*
Schematic overview of the calculation of the CoM angular acceleration (A) and proportion of foot length in contact with stair (PFLCS) (B). The CoM angular acceleration was calculated over the angle (a) between the CoM and CoP position of the trailing leg during the lowering phase. The PFLCS was calculated at touch-down using the rigid virtual shoe (orange line) as: PFLCS = (x / (x + y)) * 100%.

Figure 3. *(1.5 column fitting image)*
Example of the foot clearance calculation of the right foot. First, a two-dimensional outline of the shoe (A) was digitized and linked to three markers (first metatarsophalangeal joint: RMP1, fifth metatarsophalangeal joint: RMP5 and calcaneus lateralis: RLCL) of the static measurement (B). The virtual outline of the shoe was then projected in the movement trials (C). Foot clearance was calculated as the minimal distance between the virtual shoe and the step edge, within the *green* shaded area between *a* and *b* shown in inset D.

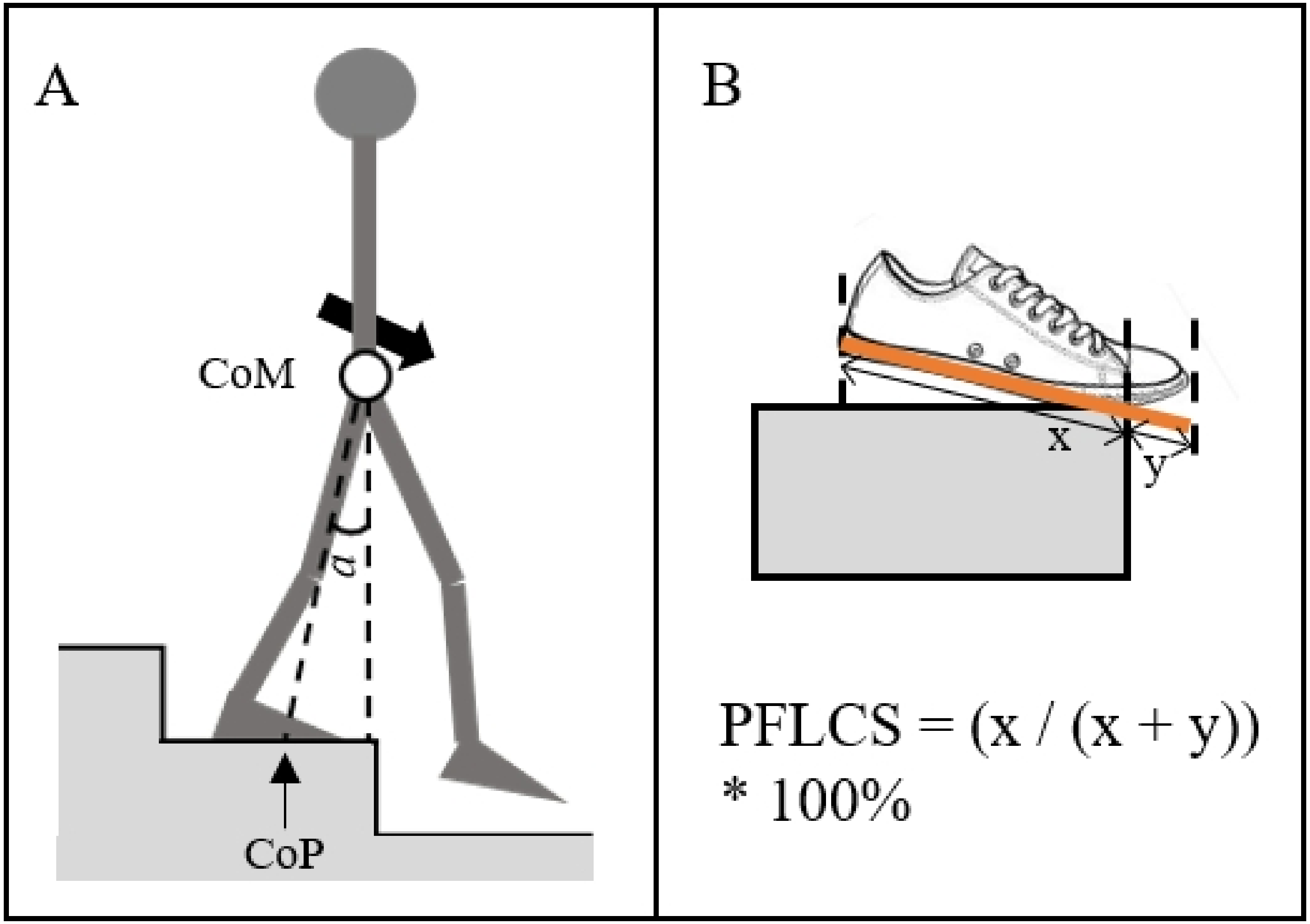
Figure 4. *(single column fitting image)*
Separation-Concordance map for the biomechanical outcome measures, highlighting the top 10% (of 500 initialisations of the k-means algorithm) ΔSSQ on the y-axis and the internal median Cramer's V on the x-axis for each value of k (2-10).

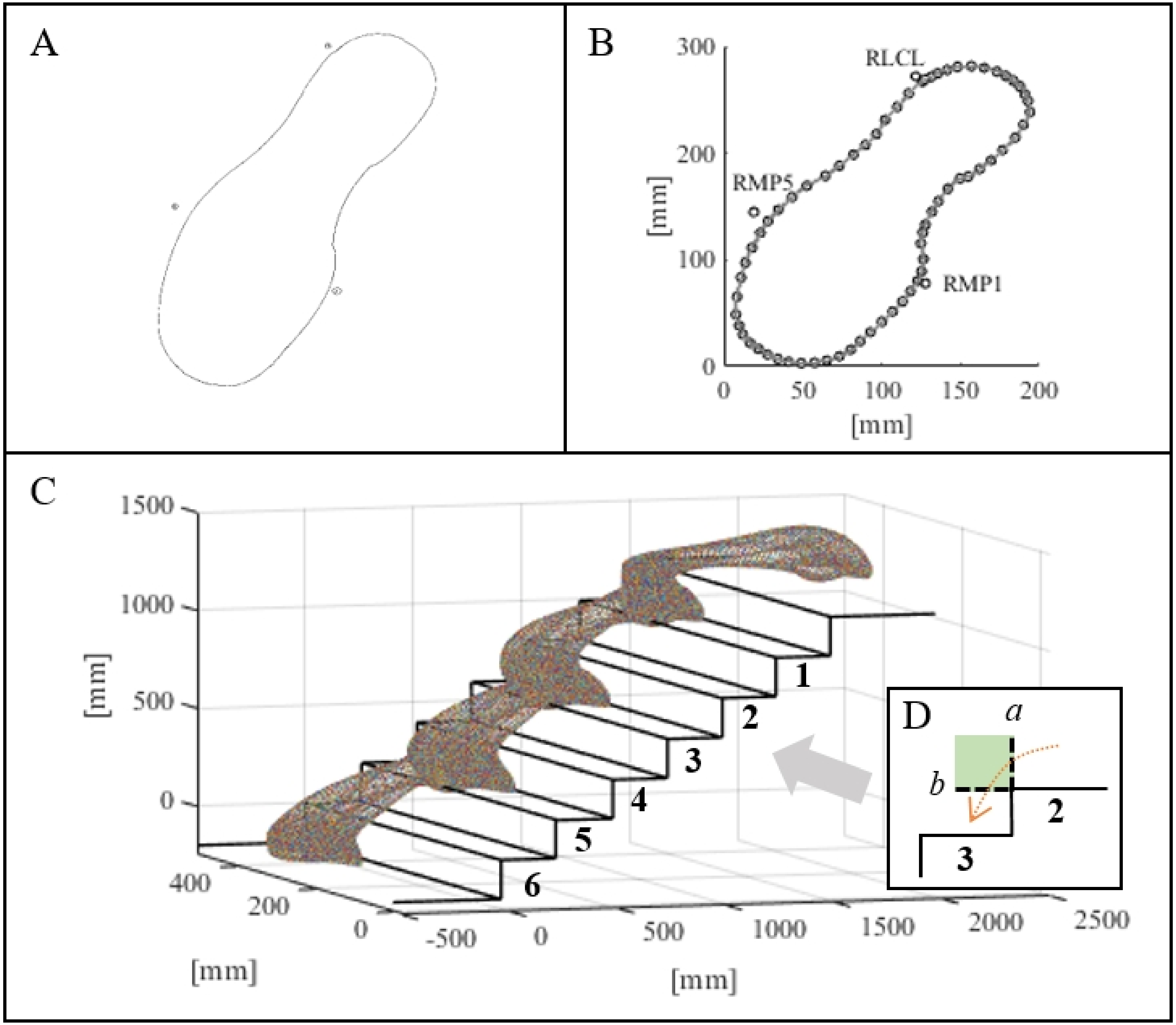
Figure 5. *(1.5 column fitting image)*

Three-dimensional plot of the first three principal components (PC1, PC2 and PC3) of the biomechanical outcome measures visualizing the segmenting clusters 1-4 including the centroids of each cluster.

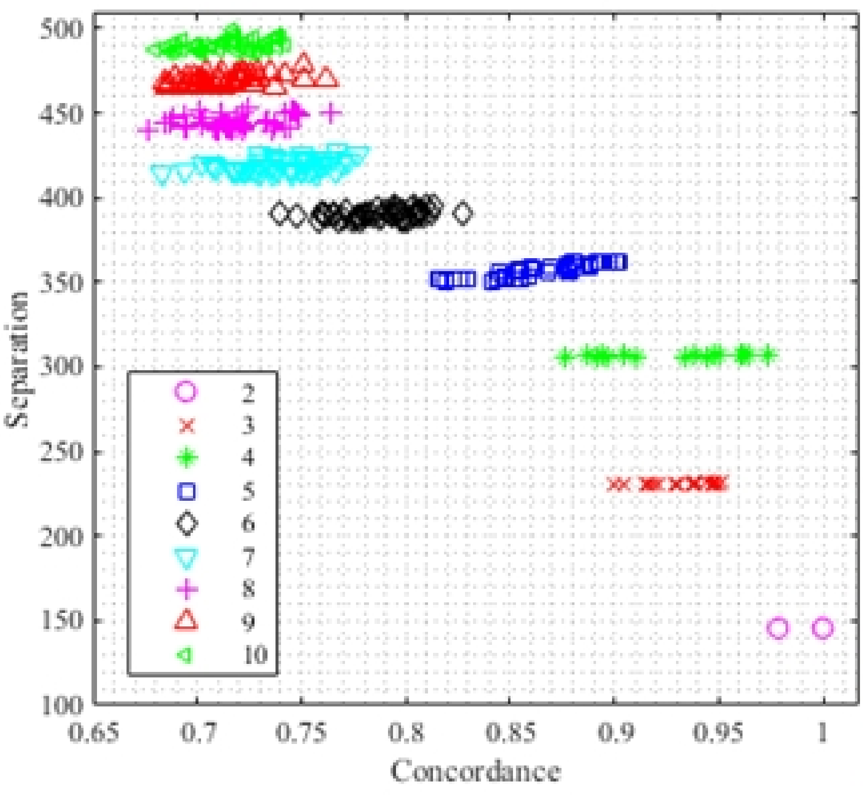


A
Overhead belay system
Top landing
Instrumented handrail
25 cm
20 cm
Force Platforms
Step 1
Step 2
Step 3
Step 4
Step 5
Step 6
Walkway
B

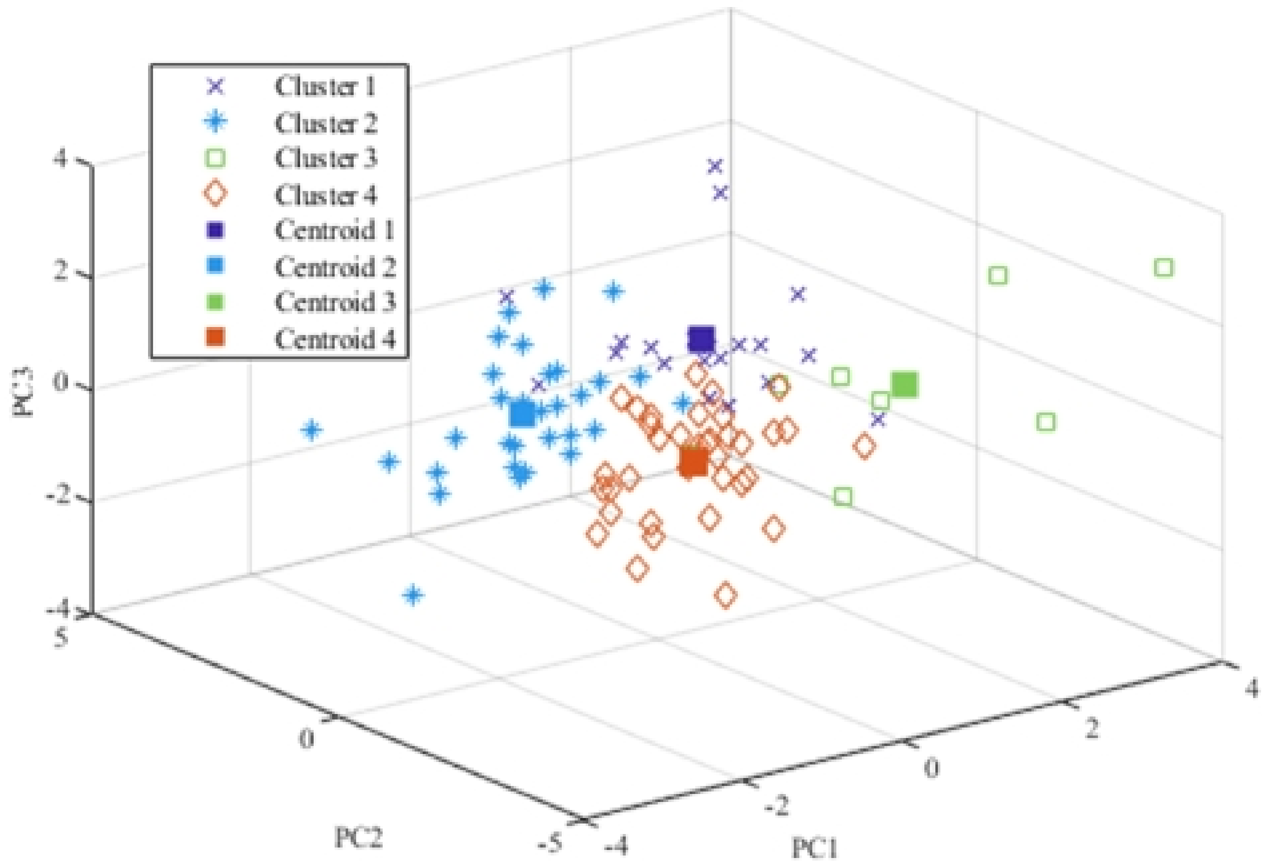

A
CoM
a
CoP
B
x
y
PFLCS = (x / (x + y))
* 100%



A
B
300
200
100
0
0
50
100
150
200
[mm]
[mm]
RLCL
RMP5
RMP1
C
1500
1000
500
0
[mm]
400
200
0
[mm]
-500
0
500
1000
1500
2000
2500
[mm]
1
2
3
4
5
6
D
a
b
2
3



Separation
Concordance
500
450
400
350
300
250
200
150
100
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
2
3
4
5
6
7
8
9
10


Cluster 1
Cluster 2
Cluster 3
Cluster 4
Centroid 1
Centroid 2
Centroid 3
Centroid 4
PC3
PC2
PC1
4
2
0
-2
-4
5
0
-5
-4
-2
0
2
4